Розроблена схема когенераційної установки, яка крім електричної і теплової енергії, виробляє метанол і кисень. Відмінною особливістю є те, що метанол виробляється з диму міні-ТЕЦ. Водень і кисень виробляються електролізом води. Електричну енергію для електролізу дає міні-ТЕЦ. Розроблено схеми автоматизації установок комплексу. Комп'ютерне моделювання та дослідження комплексу підтвердили відповідність функціонування комплексу очікуваним результатам

Ключові слова: утилізація вуглекислого газу, виробництво метанолу, кисню, електричної і теплової енергії

Разработана схема когенерационной установки, которая помимо электрической и тепловой энергии производит метанол и кислород. Отличительной особенностью является то, что метанол производится из дыма мини-ТЭЦ. Водород и кислород производятся электролизом воды. Электрическую энергию для электролиза дает мини-ТЭЦ. Разработаны схемы автоматизации установок комплекса. Компьютерное моделирование и исследование комплекса подтвердили соответствие функционирования комплекса ожидаемым результатам

Ключевые слова: утилизация углекислого газа, производство метанола, кислорода, электрической и тепловой энергии

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DESIGNING AN AUTOMATED COMPLEX BASED ON A MINI-CHP WITH RECYCLING THE FLUE GAS TO METHANOL

O. Protsyshen*
E-mail: aaprotsyshen@gmail.com
O. Stopakevych
PhD, Associate Professor*
E-mail: stopakevich@opu.ua
A. Stopakevych
PhD, Associate Professor
Department of computer-integrated technological processes and industries
Odessa National O. S. Popov Academy of Telecommunications
Kuznechna str., 1, Odessa, Ukraine, 65029
E-mail: stopakevich@gmail.com
*Department of automation of power processes
Odessa National Polytechnic University
Shevchenko ave., 1, Odessa, Ukraine, 65044

1. Introduction

A relevant scientific and technical problem is to work out solutions aimed at economically and ecologically justified energy supply development. This issue has received considerable attention both from the state and business [1].

Given the problems in the economics of gas supply, maneuvering capacities on the basis of large electric plants have become very expensive [2]. In addition, Directive 2001/80/EC prescribes to significantly reduce emission of carbon dioxide [3].

One of the directions for energy generation development, mitigating the problem, is the use of mini-CHP (cogeneration power plant) as a source of energy supply and as a nucleus of the developed solutions [4].

Economic appeal of the solutions should comprise both relatively small investment required to start the operation and proximity to the consumer, which substantially reduces operating costs and losses in the energy delivery networks.

Ecological appeal of the solutions is linked to the considerable reduction in the emissions of carbon dioxide into the atmosphere when employing the new process for its catalytic processing into methanol [5].

Economic resource for the implementation of the solutions that are being developed could be provided by an energy strategy, which imply modernisation of energy generation to reduce carbon emissions with the appropriate annual investment up to 2030 [6].

2. Literature review and problem statement

The use of mini-CHP has become one of the most promising solutions to the problem of effective heat supply and energy supply for industrial enterprises and housing and communal services in the world, as noted in article [7]. Such plants are also referred to as the two-cogeneration (or simply the cogeneration) ones, that is, those that generate two products – electricity and thermal energy. This conclusion is based on an analysis of technical and experimental data on the functioning of 11 mini-CHP, as well as the obtained actual energy and economic results of their work. Along with the mentioned results, in paper [8], it was pointed out that the advantages of mini-CHP were their relatively low cost, quick launch of their operation, proximity to customers, and combined generation of electricity and heat. It was noted that the use of mini-CHP ruled out the construction of fundamental buildings, laying and maintenance of long heat and electricity supply networks. Full computer automation of the plants and their high reliability enables autonomous operation of the plants, with less or no staff at all, as is stated in article [9]. However, the environmental problem in the functioning of mini-CHP has not been examined in the above papers.

One of the solutions to reduce carbon emissions, proposed both in article [10] and by the manufacturers of mini-CHP, is a combination of mini-CHP with a greenhouse, which is both a consumer of heat and a consumer of carbon dioxide, received by smoke purification. This approach, however, dramatically narrows the scope of mini-CHP application.

A fundamental study of the environmental problems associated with carbon emissions is the work [11]. It is pointed out that the world industry emits 30 billion tons of carbon dioxide, which is responsible for the greenhouse effect. It is emphasized that the capabilities for natural carbon dioxide disposal have been virtually exhausted. It is stated that one of the promising techniques for recycling the industrially-produced gas is its conversion into methanol.

Paper [12] described the technology of designing an automated installation for the catalytic production of methanol from carbon dioxide. It is noted that the key product in the process of methanol production is hydrogen. Methanol, produced from carbon dioxide, as noted in article [13], is advisable to use as an analogue of gasoline for fueling automobiles, which is especially convenient when using mini-CHP in small settlements. In addition, in paper [14], it was pointed out that the wholesale consumer of methanol is chemical and pharmaceutical industry. The wholesale consumption of methanol by perfume industry is described in article [15].

A review of technologies for the industrial production of hydrogen is given in paper [16]. It was noted in the review that the electrolysis of water is one of the most acceptable technologies for hydrogen production on a small scale. It was pointed out in article [17] that the most advanced technologies of hydrogen production by electrolysis provide a production of 1 nm^3 of hydrogen at a consumption of 3.75 kWh of electricity.

Thus, an analysis of the scientific literature shows that there are developed key processes, however, no single solution has been worked out, that is, a system that would generate electricity and heat, and process carbon dioxide from smoke. Additional products of the system would be methanol and oxygen. A significant amount of electricity required for the electrolysis is provided by a mini-CHP itself, which greatly simplifies implementation of the solution.

3. Research goal and objectives

The goal of present research is to develop a cogeneration plant, which, in addition to electric and thermal energy, would produce methanol and oxygen, with methanol in this case produced as a result of recycling the smoke from a mini-CHP.

To accomplish the goal, the following tasks have been set:

– to devise and examine the models of sections of the system;

– to design control loops for the automation of sections of the system.

4. Research materials and methods

The development and study of the automated system of a mini-CHP with the recycling of flue-gas into methanol were carried out using the modern universal software for technological simulation ASPEN HYSYS [18]. When entering and calculating an input model of the technological process, the software automatically employs physical-chemical ratios embedded in its libraries while the solvers automatically define feasibility of the technology, compiling material-energy balances. A key element of the model is a modern technological process of catalytic recycling of carbon dioxide, which was previously explored in papers [5, 12].

5. Results of development of the automated system of a mini-CHP with recycling flue gases into methanol

5. 1. Development and study of the models of sections of the system

Structural diagram of the system for the generation of heat and electricity with the recycling of flue-gas emissions into production of methanol and oxygen is shown in Fig. 1. The system consumes water, natural gas or biogas as fuel, generates electricity, warm water for heating for the consumer, as well as methanol and oxygen. The gases released to a smolestack contain mostly neutral nitrogen. Although the system can be calculated for any capacity of CHP, boilers, and boiler rooms, in order to obtain specific results, we selected as a basis a mini-CHP producing electricity with a capacity of eight megawatts.

In general, the installation works in the following way. Natural gas is supplied to the mini-CHP, which generates electric and thermal energy. The flue gases enter a purification unit for carbon dioxide. Electrolyser selects part of electricity from CHP for the production of hydrogen and oxygen. Oxygen is then stored in the gasholder for subsequent sale. Through the compressor and mixer, the mixture of CO_2 and H_2 enters the section for methanol synthesis. Next, the flow mixes with a recycle, it is heated and fed to the reactor. After the reactor, a mixture of CO_2, H_2, H_2O and CH_3OH is cooled with methanol and water separated in the separator, which then enter the section of rectification while the gases are fed to recycling. Upon the rectification, we receive pure methanol and water. Methanol is delivered to the warehouse.

We shall simulate the operation of the system to determine the mode parameters of all installations, to verify material and energy balances, catalytic chemical reactions. Modeling will be conducted for the basic settings of the system, coordinating the input and output flows. Such auxiliary installations as a gasholder, warehouse for methanol, a cooling tower will not be simulated since their modeling is rather obvious while the operation of these installations has virtually no effect on the technological processes that are of interest to us.

A model of the mini-CHP is shown in Fig. 2. The model is designed in accordance with the recommendations on modelling a cogeneration unit, outlined in article [19]. A mini-CHP includes an engine running on natural gas, an electricity generator, a heat exchanger for recycling the heat of flue gases into water heating.

As a result of simulation, we obtained the following basic flow parameters:

– natural gas (consumption 749.5 kg/h, temperature 20 °C);

– air (consumption 15,760 kg/h; temperature 20 °C);

– water to consumer (consumption 47,000 kg/h; temperature 90 °C, 3 MW);

– electricity from generator (8 MW);

– flue gases (consumption 16,510 kg/h; temperature 40 °C).

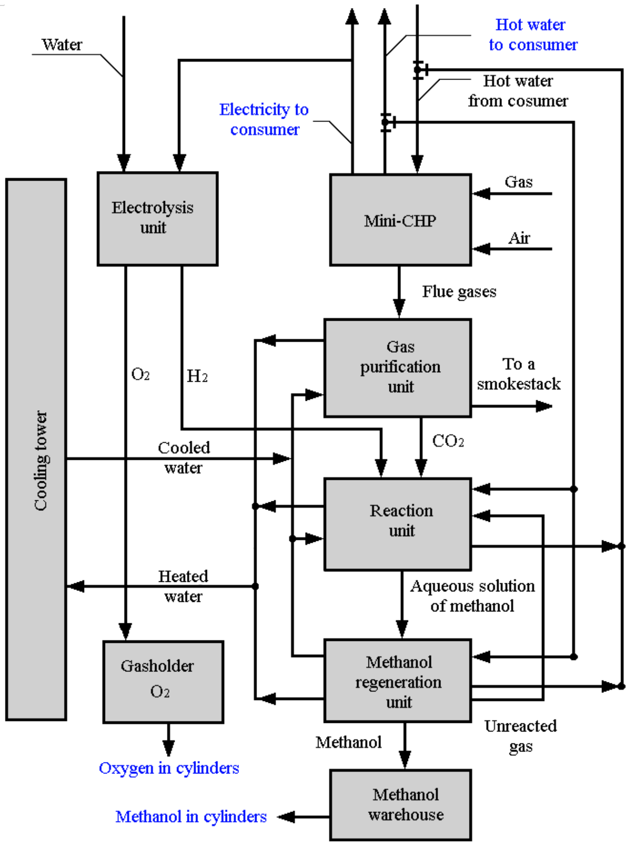

Fig. 1. Structural diagram of the automated system for generating heat and electricity with the recycling of flue gas emissions

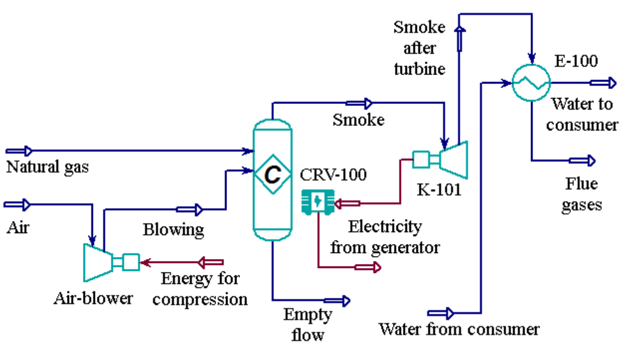

Fig. 2. Simulation diagram of mini-CHP

A model of the gas purification unit is shown in Fig. 3. The model is designed in accordance with the recommendations on modelling an absorption installation, outlined in paper [20].

The unit works in the following way. Carbon dioxide is released from the flue gases via absorption by aqueous solution of monoethanolamine (MEA) in the absorber with the subsequent regeneration of absorbent in the desorber. The purified carbon dioxide is sent for further recycling. The off-gases are released into a smokestack. Given that part of the MEA is carried away, there is an additional supply of the MEA solution.

As a result of simulation, we obtained the following basic flow parameters:

– flue gases (consumption 16,510 kg/h; temperature 40 °C);

– CO_2 (consumption 880 kg/h, temperature 40 °C, pressure 4 MPa);

– MEA (5.1 kg/h);

– water (10.75 kg/h);

– off-gases into a smokestack (5,535 kg/h);

– energy consumption for cooling (661 kW);

– energy consumption for electricity (0.84 kW).

An integrated model of the reaction plant, methanol regeneration unit and the electrolysis unit is shown in Fig. 4. The model of the reaction plant and the methanol regeneration unit are designed in accordance with the results obtained in article [5]. The electrolysis unit's model is designed in accordance with the recommendations on modeling outlined in paper [21].

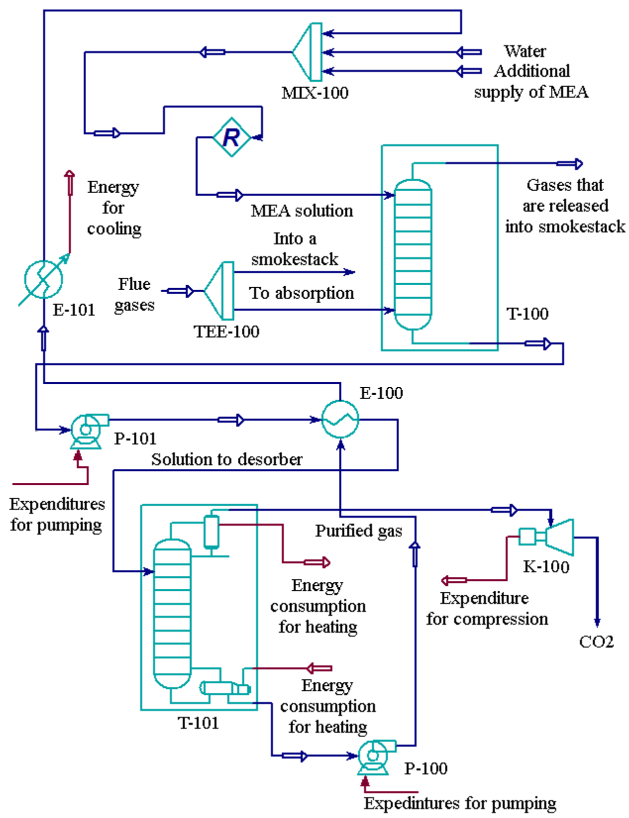

Fig. 3. Simulation diagram of the gas purification unit

A scheme of the catalytic chemical reaction of methanol synthesis is $CO_2+3H_2=CH_3OH+H_2O$. In the reactor, the catalyst takes up the entire cross-section of the apparatus and it is arranged in layers on horizontal grids. The reactor design allows the use of selective and copper-zinc catalysts employed in the synthesis. From the reactor, gas enters the refrigerator where it is cooled to 40 °C, and then the separator, where methanol is separated from the unreacted gases. The gases are directed to the booster compressor, and the process starts over again. After the synthesis and cooling, the water-methanol solution enters regeneration unit. The heat required for the regeneration is supplied from the reboiler. Methanol vapors are condensed in the cooler at the top of the column. Irrigation is provided by the pump. Regenerated methanol is cooled in a heat exchanger and is sent for storage. In order to obtain hydrogen, we selected the electrolyser with the following characteristics: working excess pressure 0.01 MPa, current 7800–8200 A, voltage 380 V, specific power consumption 5.2 kWh/m^3, hydrogen purity 99.5 %, oxygen purity 98.5 %. The process requires 120 kg/h or 1.333 m^3/h of hydrogen, which needs 7.094 kW of electric power from the mini-CHP.

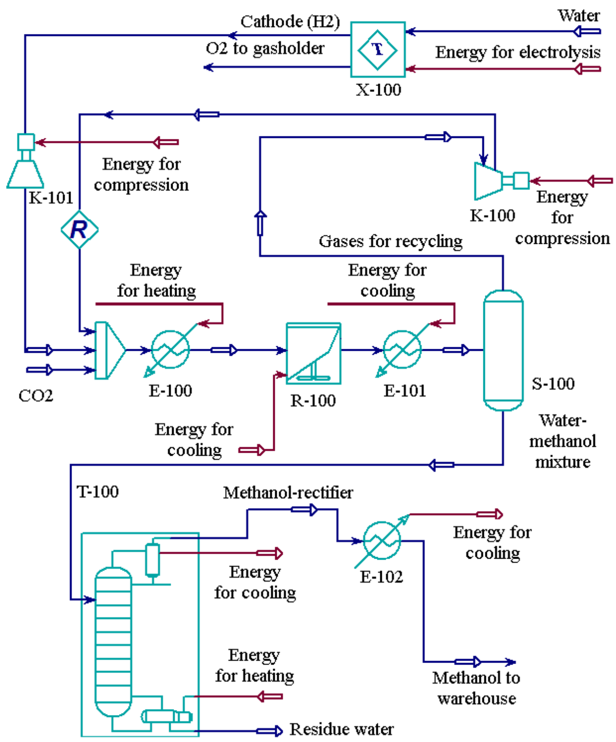

Fig. 4. Simulation diagram of the reaction plant, methanol regeneration unit and electrolysis unit

As a result of computer simulation of the system, Fig. 4, we obtained the following flow parameters:

– CO_2 (pressure – 4 MPa, temperature 40 °C, mass flow rate 880 kg/h);

– water (1,080 kg/h);

– energy for electrolysis (7,094 kW);

– residual water (344.3 kg/h);

– O_2 to gasholder (960 kg/h);

– methanol to warehouse (625.5 kg/h).

Thus, computer simulation of the system that we performed allowed us to obtain parameters of the basic flows and to confirm feasibility of the utilized technological processes.

5. 2. Development of automation systems of sections of the complex

Operation of the complex is impossible without maintaining basic mode parameters of the installations by the automation systems since computer simulation reveals a dependence of the complex performance on the deviations of these parameters.

The developed automation systems imply the use of centralized computer control under a real-time operating system, applied software for the implementation of control system and control over a SCADA-system, which matches contemporary trends in the field of production automation [12]. The choice of automation means is not considered, but it is recommended to select reliable and accurate means of automation with the industrial network interface RS-485. This makes it possible to employ a minimum number of elements in a computer automation system and improves its performance reliability.

An automation system of a mini-CHP (Fig. 5) implies stabilization of the following parameters:

– temperature of the flue gases to the purification unit (40 °C);

– current frequency from a generator (50 Hz);

– temperature of heated water to the consumer (90 °C).

The quantity and the temperature of hot water supplied to the consumer, as well as the amount of generated electricity are to be taken into consideration.

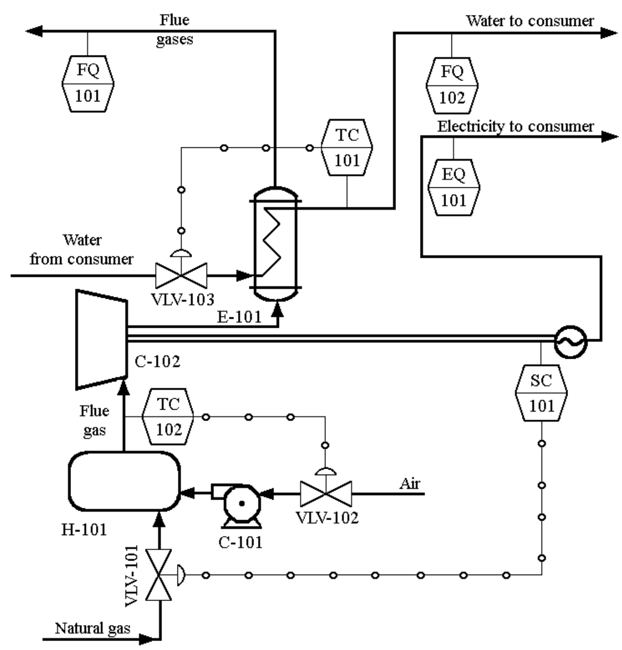

Fig. 5. Automation system of the mini-CHPP: C-101 – air-blower; C-102 – turbine; E-101 – heat exchanger; H-101 – combustion chamber

An automation system of a flue gas purification unit (Fig. 6) implies stabilization of the following parameters:

– pressure at the top of the absorber (115 kPa);

– desorber's temperature (130 °C);

– temperature at the inlet to the absorber (40 °C);

– CO_2 temperature at the outlet of the unit (40 °C).

The amount of CO_2 supplied to the reaction installation is to be taken into consideration.

Automation system of the reactor for methanol synthesis (Fig. 7) implies stabilization of the temperature of the starting mixture and the temperature of the aqueous solution of methanol at the outlet of the reactor (40 °C).

Automation system of the methanol regeneration unit (Fig. 8) implies stabilization of the following parameters: level in the condenser, level in the column cube, concentration of methanol in the upper product, methanol concentration in the bottom product. The amount of the produced commercial methanol is to be taken account of. Distillation column is a complex multidimensional object. In article [5], authors performed a research into two systems of the automated control over the distillation column considered using a nonlinear model. Simulation results show the advantage of employing a predictive modeling controller for the examined case.

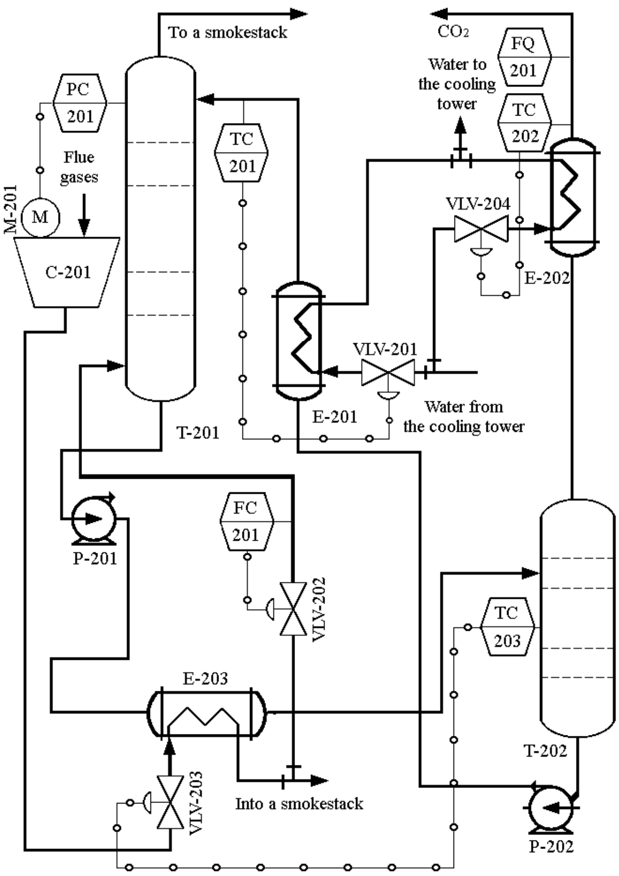

Fig. 6. Automation system for the gas purification unit: T-201 – absorber; T-202 – desorber; P-201, P-202 – pumps; E-201 – cooler; E-202, E-203 – heaters

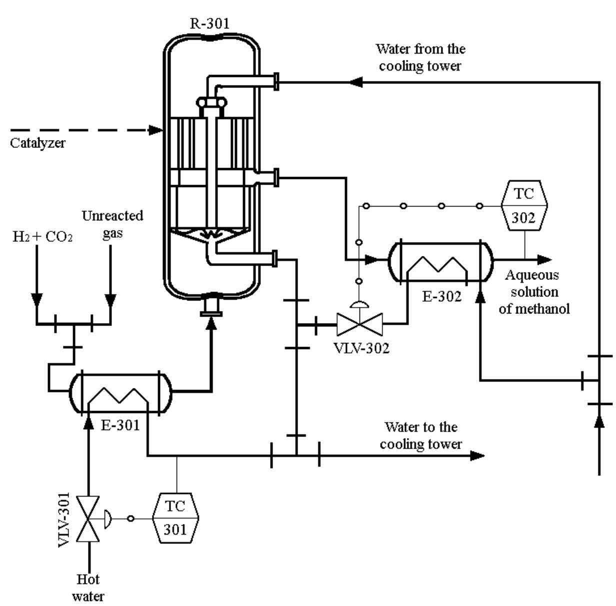

Fig. 7. Automation system of the methanol synthesis reactor: R-301 – reactor; E-301 – heater of the mixture to the reaction temperature; E-302 – cooler of the water-methanol mixture

Automation system of the electrolyser (Fig. 9) implies stabilization of the electrolysis current. By using a manual control, it is possible to blow storage tanks for oxygen and hydrogen. The amount of the received water and electricity is to be taken account of.

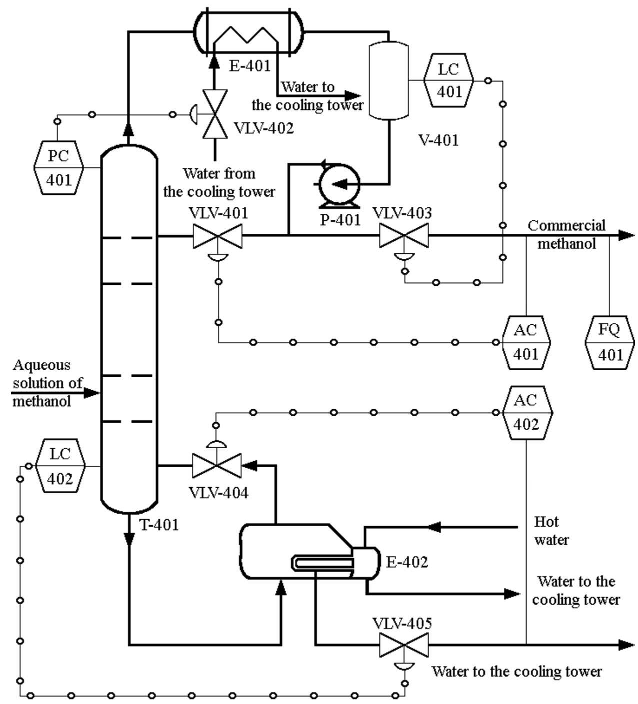

Fig. 8. Automation system of the methanol regeneration unit: T-401 – distillation column; E-401 – methanol cooler; E-402 – reboiler; V-401 – capacitor; P-401 – pump for supplying the reflux

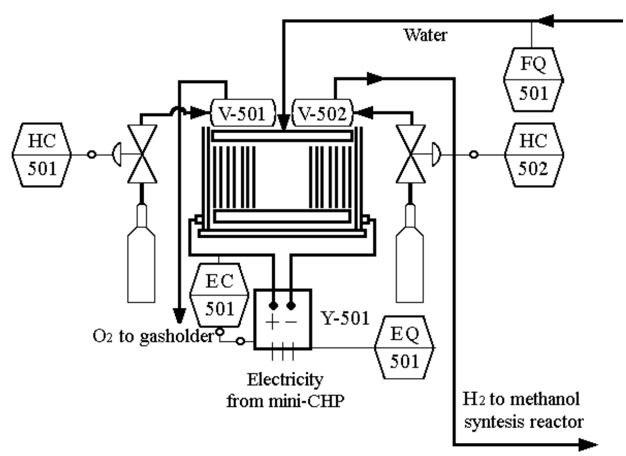

Fig. 9. Automation system of the electrolyser: V-501 – oxygen gas-collector; V-502 – hydrogen gas-collector; X-501 – electrolyser; Y-501 – controlled thyristor rectifier

Automation system of the gasholder (Fig. 10) implies gas pressure measurement in the gasholder and in the pressurized pipeline of the compressor. Oxygen cylinders filling is carried out manually.

Automation system of the cooling tower (Fig. 11) implies implementation of a combined control system. The system stabilizes the outlet water temperature, taking into account a measurement of the water flow rate at the outlet, temperature of incoming water, ambient temperature and humidity. The principle of implementation of such a system is examined in paper [22].

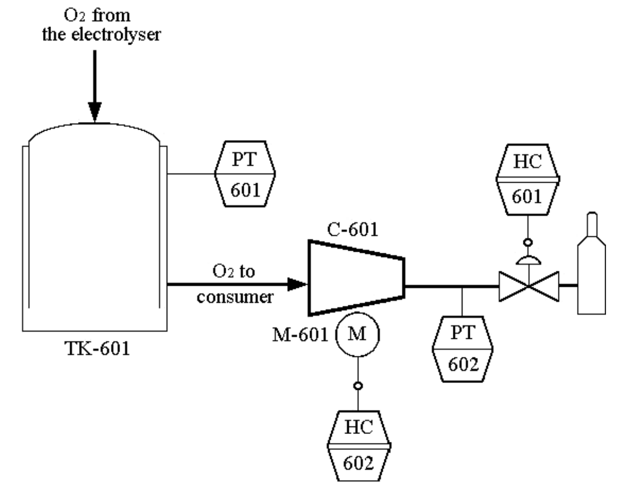

Fig. 10. Automation system of the gasholder: TK-601 – gasholder; C-601 – compressor O_2

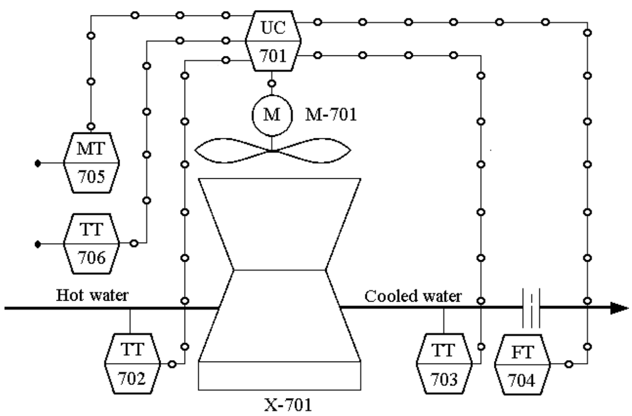

Fig. 11. Automation system of the cooling tower: X-701 – cooling tower; M-701 – fan

Automation system of the methanol warehouse (Fig. 12) implies measuring the pressure and level in the methanol storage tank, pressure in the pressurized pipeline of the pump. Filling of methanol in cylinders is carried out manually.

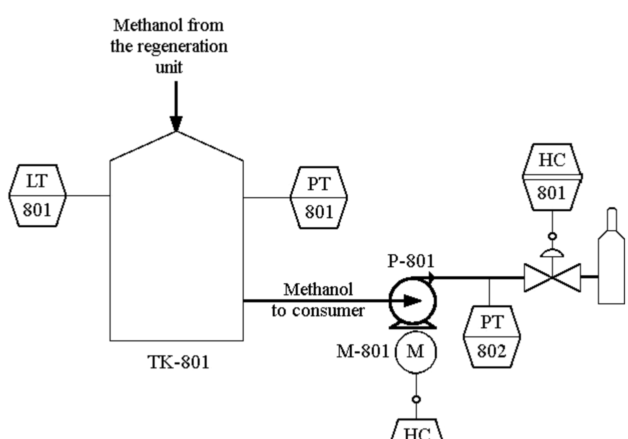

Fig. 12. Automation system of the methanol warehouse: TK-801 – tank with methanol

In addition to the described control loops, the automation is to be applied to the operations of launching and terminating the system, to the analysis of emergency situations. These operations are not considered in the present study.

6. Discussion of results of development of the automated system

1. The development of cogeneration plants of various types is a relevant task, because it allows improvement in efficiency and provides implementation of additional functions. Typical solution is a combination of the mini-CHP with greenhouses [10], but this solution largely restricts the scope of application of the plants. More effective is to design plants that would make it possible, along with electric and thermal energy, to produce additional much-needed products. Such products in the installation whose we designed are methanol and oxygen.

2. The developed cogeneration plant employs a catalytic technological process for methanol production, which enables recycling of the flue gas emissions from a mini-CHP. Such an approach predetermines ecological compatibility of the proposed solution.

3. Hydrogen and oxygen in the proposed structure are produced by the electrolysis of water. Electricity for the electrolysis is provided by a mini-CHP. Hydrogen is used in the catalytic synthesis of methanol while oxygen is the product popular among consumers.

4. Design and study of the sections of a cogeneration plant were conducted using modern universal software for technological simulation. When modeling sections of the plant, we applied results and recommendations from the studies on technology and modeling of mini-CHP [19], absorption unit [20], reaction plant with methanol regeneration [5, 12], and electrolyser [21]. The computer simulation of the system that we performed allowed us to obtain all parameters of the basic flows of the plant's sections, which confirm consistency of the calculations and the possibility of technical implementation of the plant.

5. Results of the computer simulation show the dependence of the system's performance on the deviation of mode parameters. Stabilization of mode parameters is achieved using the devised automation systems. Automation systems could form the basis for design documentation of the automation system of a cogeneration plant. The automation system's structure that we developed is designed for computer control and requires minimal maintenance personnel, which is in line with contemporary trends in the automation of cogeneration plants.

7. Conclusions

1. We developed a four-cogeneration plant, which, in addition to electric and thermal energy, produces methanol and oxygen; in this case, methanol is produced as a result of the recycling of smoke from a mini-CHP. The simulation models are devised for all sections of the cogeneration unit. The values of parameters for basic flows of the plant are given, which were obtained during simulation. Simulation results confirm the possibility of employing the developed plant.

2. We designed automation systems of all sections of the cogeneration unit. Based on the results of computer simulation, the parameters are selected that maintain productivity of the plant and quality of the output products at a deviation of the value of mode parameters. Furthermore, the control loops imply accounting of the resources consumed and produced by the plant.

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